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INTERACTION BETWEEN A SHOCK WAVE AND A VORTEX

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16. Abstract

Experimental investigations of the interaction between a shock wave and a vortex were made in a large shock tube. High-speed Schlieren photography made it possible to observe the evolution of the phenomena. The theoretical discussion considers the general problem of the interaction between a discontinuity and any type of perturbation.

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When an isolated vortex encounters a shock wave, a sound wave /1* is produced. Study of this phenomenon is especially valuable since it is related to numerous problems of aerodynamics and acoustics (jet engine and rocket engine noise, noise associated with helicopter blades, etc.).

Experimental Study

A large shock tube was used (length 18 m, cross section 0.08 x 0.16). The isolated vortex was produced by the flow of air (subsonic in our experiments) immediately following the shock wave occurring in the low-pressure chamber on an airfoil placed at a 5° angle. The primary shock wave was relected by the end of the low-pressure chamber of the tube and encountered, within the observation field, the vortex separated from the trailing edge of the model and entrained by the air flow.

Observations were made by schlieren photography and pluviometry by means of a high-speed electronic camera taking a series of 16 successive photographs at a rate of 500,000 images/second. Each photograph was then reproduced a given number of times (depending on the slowdown desired) on 16 mm film by means of an ordinary /2
camera. In this way a virtually continuous film with very broad slowdown of the phenomenon was obtained. The most important observations from this film were deformation of the shock wave following interaction and the formation of a wave propagating at the speed of sound, centered on the transmitted vortex and having four successive zones of increasing and decreasing density along its

* Numbers in the margin indicate pagination in the foreign text.

front.

The display methods used made it possible to identify the sites where the variations in the index of refraction (related to specific mass) were maximum, minimum or zero.

Cinematography was used to observe the evolution and measure the velocities of the various perturbations.

Theoretical Analysis

The interaction of a shock wave with a vortex is considered to be only a special case of the general problem of the interaction of any given perturbation with a discontinuity.

All perturbations may be divided into three basic types:

1. A pressure perturbation moving at the local velocity of sound and entrained by the principal flow, represented by isoentropic longitudinal waves.

2. A perturbation of rotational velocity entrained by the principal flow and represented by isentropic transverse shear waves.

3. A perturbation of rotational entropy entrained by the principal flow and represented by transverse waves.

The interaction of any one of these three basic perturbations with a shock wave results in the simultaneous formation of three basic perturbations behind the shock wave, as well as deformation of this wave.

Considering a slight arbitrary perturbation of one of these three types, the spatial distribution may be represented by a superposition, or a spectrum, of sinusoidal flat waves (longitudinal or transverse) distributed over all orientations and wavelengths. (This is a physical interpretation of the mathematical formulation of the Fourier integral.) Specifically, the rotational velocity field of the separated vortex:

$$q(r,t) = \frac{\Gamma}{2\pi r}\left[1 - e^{-\frac{r^2}{4\nu t}}\right]$$

in which Γ = flow around the model;

r = radial distance;

and ν = viscosity;

is decomposed into elementary flat shear waves. The interaction /3 of this shock wave with each of these elementary flat waves may be analyzed within a suitable system of reference axes which place the problem in a steady state (stationary elementary shock waves and ripple).

The conditions at the limits (relations of oblique shock wave) and the differential equation of disturbed flow allow for the deformation of the unknown shock wave. All these magnitudes may therefore be expressed in non-linear form following interaction by means of linear functions: either a single variable $_i/\bar{u}_c$ (transverse shear wave) or two variables $_i/\bar{u}_c$ and $p_i/\bar{p}_e$ (longitudinal pressure wave).

Solving of the differential equation results in a system of linear equations behind the shock wave.

Numerical integration in all directions and with all wave numbers yields the total field and the final deformation of the shock wave after interaction.

This method of analysis may be generalized to all types of perturbation and discontinuity.

In the case of interaction between a vortex and a shock wave, numerical solutions were obtained for different intensities.

These theoretical analyses were then compared with the experimental findings.

Abstract /4

The interaction between a shock wave and a vortex generates a sound wave centered on the vortex whose front contains four alternating zones of compression and expansion.

The experiments were performed in a large shock tube. The use of a high-speed electronic camera incorporated in a schlieren photographic or pluviometric optical assembly made it possible to observe the evolution of the phenomenon, to pinpoint variations in specific mass and to measure the velocities of the waves.

A 16 mm film obtained by reproducing the individual photographs permitted observation at a much slower speed.

Theoretical analysis of this problem led to consideration of the general case of the interaction of any given perturbation with a discontinuity.

This type of study is especially valuable in that it makes it possible to determine the process of emission of sound waves by supersonic gas jets, the noise associated with helicopter blades, and many other aerodynamic and acoustic problems.